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ABSTRACT

We present results from the Sustained Spheromak Physics Experiment (SSPX) at LLNL, which has been built to study energy confinement in spheromak plasmas sustained for up to 2 ms by coaxial DC helicity injection. Peak toroidal currents as high as 600kA have been obtained in the 1m dia. (0.23m minor radius) device using injection currents between 200–400kA; these currents generate edge poloidal fields in the range of 0.2–0.4T. The internal field and current profiles are inferred from edge field measurements using the CORSICA code. Density and impurity control is obtained using baking, glow discharge cleansing, and titanium gettering, after which long plasma decay times ($\tau \geq 1.5$ms) are observed and impurity radiation losses are reduced from ~50% to <20% of the input energy. Thomson scattering measurements show peaked electron temperature and pressure profiles with T_e (0)~120eV and β_e~7%. Edge field measurements show the presence of n=1 modes during the formation phase, as has been observed in other spheromaks. This mode dies away during sustainment and decay so that edge fluctuation levels as low as 1% have been measured. These results are compared with numerical simulations using the NIMROD code.

1.0 Introduction

In this paper we present results of formation and sustainment experiments in the SSPX spheromak now operating at LLNL, and discuss nonlinear 3-d MHD simulations of the buildup using the NIMROD code[1]. Recently, improved wall conditioning has yielded plasmas with long decay times, which are not dominated by radiative losses. The SSPX device (Sustained Spheromak Physics Experiment) was designed to study energy confinement and magnetic fluctuations in a spheromak plasma sustained by coaxial helicity injection. The spheromak potentially offers significant advantages for a fusion reactor because it is compact, free of field coils linking the vacuum vessel, and can be operated in steady state with helicity injection. It has been predicted [2] that the core energy confinement in such a device will increase with increasing electron temperature, since the fluctuation level needed to transport helicity inward from the edge is reduced as the plasma resistivity falls. New features of SSPX include a large-radius coaxial injector to improve drive efficiency, a set of programmable bias magnetic field coils to vary the magnetic geometry, a conformal flux conserver to minimize open field lines near the plasma, and a divertor to aid in particle exhaust.

The main issue for the spheromak as a reactor concept is the energy confinement in the presence of magnetic fluctuations which are necessary to transport helicity (interconnected flux) into the core of the spheromak to maintain the Taylor-state field configuration. These modes break axisymmetry and open the equilibrium magnetic surfaces, allowing energy to leak from the spheromak core. Recent scaling studies by Fowler[2] and Hooper[3], including data from previous experiments, indicate that this turbulence should weaken with increasing electron temperature fast enough to give acceptable confinement times for reactor-relevant conditions. However, the scaling of the fluctuation amplitude ($\tilde{B}/B$) and resulting transport

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with $S = \tau_R/\tau_A \propto BT_e^{3/2}$ is not known for the spheromak. This is a central theme of the SSPX experimental and theoretical programs at LLNL.

2. The SSPX Device and Operation

The SSPX device produces 1.5–2.0 msec spheromak plasmas with an outer dia. of 1m and a plasma minor radius of 23cm. A cross section of the device, along with a representative CORSICA 2-d MHD equilibrium[4], is shown in Fig. 1. The plasma is contained by the 1.2cm thick copper flux conserver, whose surfaces have been coated with plasma-sprayed tungsten to minimize sputtering. The spheromak is powered by a 0.5MJ 10kV formation bank which is fired approximately 0.25ms after 2 Torr-l of hydrogen gas is injected into the coaxial region as shown; a second, 5kV, 1.5MJ sustainment bank fires approximately 0.25msec after the initial breakdown. Prior to operation, the vessel is baked for 120hrs, with hydrogen GDC operating during the last 20hrs of the bake. During operation, titanium gettering is applied before every third discharge. These procedures result in a clean ($E_{rad}/E_{input} < 0.2$), low density ($n_e=1\times10^{19}m^{-3}$) discharge with high normalized current ($j/n > 10^{-14}$ A-m). VUV spectroscopy shows oxygen to be the main radiator in these discharges[5].

The coaxial injector of SSPX differs from that of previous experiments in that it has a relatively large radius ($R_{inj}\sim R_{fc}$), lacks a transition region, and has the vacuum field spanning it radially. These features are predicted[6] to improve energy efficiency and minimize open field lines in the main plasma region. So far, we are finding an energy efficiency ($W_p/E_{in}=\int B^2dV/\int IVdt$) of about 15%, which is in line with previous experiments such as CTX. However, the measured magnetic flux pulled from the gun is less than 50% of the initial vacuum flux, so we are not taking full advantage of this configuration. The reduced flux utilization likely results from the fact that a number of field lines cross the gun above the region where initial breakdown takes place (see Fig. 1) and that the field strength decreases towards the flux conserver. The decreasing field strength also smears out the spheromak formation threshold so that we can form very low field spheromaks even when the injector current is well below the predicted threshold of $I_{th} = \lambda_{inj}\psi_{inj}$, where ψ_{inj} is the magnetic flux and $\lambda_{inj} = \pi/\text{gap\_width} = 19.6m^{-1}$ for SSPX.

After the formation phase, we infer the current and field profiles of the resulting spheromak by using the CORSICA code to find 2d MHD equilibria consistent with the edge poloidal field measurements (at nine locations) and the injector current. The low aspect ratio of the spheromak makes it possible to extract some idea of the current profile from external measurements alone. Typically, we find a good fit to the probe data with a current density of the form $\mu_0 j/B=\lambda(\psi)=\lambda_o(1+\lambda^n)$, with λ_{sol} about twice that in the core plasma during the driven phase when $I>I_{thresh}$. Inside the separatrix λ is nearly flat and q is below unity as expected. During the decay phase, the fields are consistent with the Bessel Function Model of the Taylor relaxed-state[7], but deviate significantly as time progresses. In the future, a Transient Internal Probe will be used to measure the internal toroidal field profile[8] via Faraday rotation of laser light inside a small bullet of high-Verdet constant glass passing through the plasma at 1.5km/s.

3. Helicity and Energy Balance

The central focus of our research is on maintaining good energy confinement while the plasma is sustained by coaxial helicity injection. So far, we have carried out preliminary experiments to look at sustainment in two different magnetic configurations. We obtain the best results (highest internal fields) using a field geometry in which about 25% of the initial magnetic flux passes vertically down through the flux conserver rather than across the injector gap. This "modified flux" configuration allows current to flow along the geometric axis without first having to bend the field lines in the injector (the usual "bubble burst" criteria). As a result, the spheromak formation threshold is lowered by about 50%, to $\lambda_{th} = \lambda_{fc} = 10m^{-1}$. The peak edge poloidal fields are approximately 15% higher than for similar discharges with the standard flux configuration. In the future, new bias field coils will allow us to pull all the initial magnetic flux down the axis

With the additional energy and helicity input from the sustainment bank, the discharge lasts much longer than it would with the formation bank alone. A typical "best" sustained discharge in the modified flux configuration is shown in Fig. 2. Such discharges are characterized by a low injector voltage (about 10% of the peak formation voltage), steady midplane poloidal fields and line-average density, low edge magnetic fluctuations, and slowly decaying total field energy and toroidal current. Differentiating between a marginally sustained and decaying spheromak plasma can be difficult when the L/R time of the discharge is longer than the pulse length (L/R > 10msec for these conditions, assuming no plasma cooling during decay) and when the input power may be largely dissipated on the open field lines in the edge plasma. Usually we assume that the plasma is being sustained when n=1 magnetic fluctuations are observed, and that it is decaying when n=2 modes are seen (the n=2 signifying a peaked current profile indicative of resistive decay on the outer flux surfaces. The discharge shown here exhibits both of these features.

Helicity balance is a central underpinning of spheromak physics. With coaxial helicity injection as in SSPX, the helicity input is simply $2V_{inj}\Psi_{inj}$, where V is the electrode voltage and p is the magnetic flux linked by the injection current. The total helicity balance is then given by $dK/dt = 2V_{inj}\Psi_{inj} - K/\tau_K$, where K is the total helicity determined using CORSICA to integrate the linked flux, and τ_K is the helicity decay time. We have examined helicity balance in SSPX and find that careful accounting for the magnetic configuration and injector physics is needed to obtain balance. For example, in SSPX we capture only a fraction of the nominal injector magnetic flux, so the helicity input is reduced. The fraction of captured flux is not well known and may vary in time. Furthermore, the presence of a large sheath voltage drop in the gun may reduce the effectiveness of the applied voltage (or equivalently, introduce a large dissipation). The effect of the sheath on the helicity balance is hard to model because the applied voltage changes with time during the pulse (see Fig. 2). Finally, the helicity decay time very likely changes throughout the pulse. In the end, we can obtain helicity balance to within about 10-20% without subtracting the sheath voltage by assuming that the helicity decay time is of the order of 1.5ms and that we utilize only about 30% of the injector magnetic flux.

Peaked density and electron temperature profiles are measured in SSPX using a 10 channel 1.6J Nd:YAG Thomson scattering system which has been designed to measure Te in the range 10eV – 1keV. The profile data (spanning from the outer edge to the geometric axis at R=0) are obtained at a single time point, but temporal evolution can be studied by varying the timing of the laser pulse on a shot-by-shot basis for a series of identical discharges. Fig. 3 shows the temperature, density, and pressure profiles for a discharge with a time history similar to that in Fig. 2. Peak temperatures reach 120eV on the magnetic axis; significantly, data from inside and outside the axis match when mapped to flux surfaces. Here we have used CORSICA to determine the local B-field from which the local β_e is derived (recall that there is no vacuum magnetic field inside the flux conserver, so we use the self-generated spheromak field). The density profile has been normalized against the line-averaged density measured by a CO_2 interferometer. The peak electron pressure, $\beta_e \sim 7\%$ (implying $\beta_{tot} \sim 14\%$ if $T_i = T_e$), is well above the Mercier limit, as has been noted[9] in other spheromak experiments.

We can estimate the energy confinement time from the measured T_e and n_e profiles if we know the input power. For the ohmically heated spheromak, this amounts to calculating ηj^2 throughout the volume, which we do using CORSICA, assuming classical Spitzer resistivity ($\propto T^{3/2}$) with Z_{eff}=2.3. As expected, the global energy confinement time ($\tau_e \sim 70\mu s$) is dominated by edge heating and losses where T_e is low; in fact, the central confinement time may be up to six times higher if the resistivity is a function of T_e alone. Also, since the peak temperature is maintained throughout much of the pulse (it starts at 60eV during formation and begins to decay only late in the pulse), we conclude that we continue to couple energy into the confined plasma via the coaxial injector in spite of the absence of large n=1 fluctuations and in spite of the fact the $\lambda_{inj} \leq \lambda_{fc}$ during this time.

4. Numerical Simulation of SSPX Plasmas

At the fundamental level, we have started to examine how edge-current fluctuations during sustainment can be related to the plasma dynamo. In these studies, we use discrete Fourier analysis, and also a new Phase Velocity Transform (PVT) technique[10] to uncover the structure of the fluctuations. The PVT analysis shows the principal mode to be nonsinusoidal (see Fig. 4) with $n = 1$, $n = 3$, and very weak $n = 2$ components. As time progresses during the pulse, the n =1 mode dies away and is replaced by an n =2 mode during the decay phase.

We are also using the NIMROD code to carry out 3-d time-dependent, nonlinear MHD simulations of spheromak plasma evolution in a realistic SSPX-like geometry with coaxial helicity injection. We find that the code results agree qualitatively with CORSICA simulations and SSPX data; e.g., q(r) and mode activity, reasonable $\lambda(r)$ profiles, j(r), $\Psi(r)$, and B(r) magnitudes and profiles, and reduced asymmetries during the decay phase. Representative PVT analysis of NIMROD results appear in Fig. 4 and may be compared with the experimental data; the n =1 structure is present, but the amplitude of the other low order modes is much higher than in SSPX. NIMROD is also being used to examine the formation of closed flux surfaces in the spheromak, which we know will have a large impact on energy confinement. Surface-of-section plots of the magnetic field lines show < 10 toroidal transits on most spheromak "flux surfaces" when driven at constant voltage, with much longer lengths (~40+ transits) appearing after the voltage starts to ramp down during the decay phase. These lengths are somewhat shorter than estimates based on open-field line power balance (40 – 90 transits) and may be inconsistent with T_e profile data, which exhibit pressure balance on CORSICA 2d flux surfaces. The relationship between toroidally (or temporally) averaged quantities and the detailed topology of the field lines in the spheromak, and how this affects particle and energy transport, are some of the fundamental questions which must be answered for us to understand the confinement properties of these devices.

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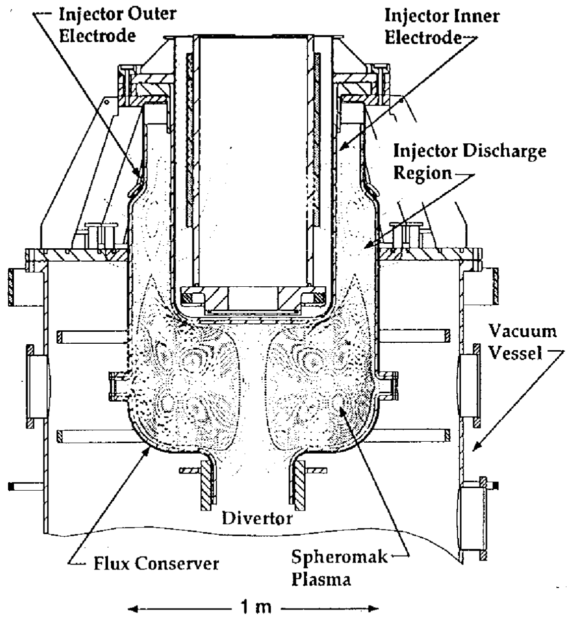

Fig 1 Cross section of SSPX spheromak.

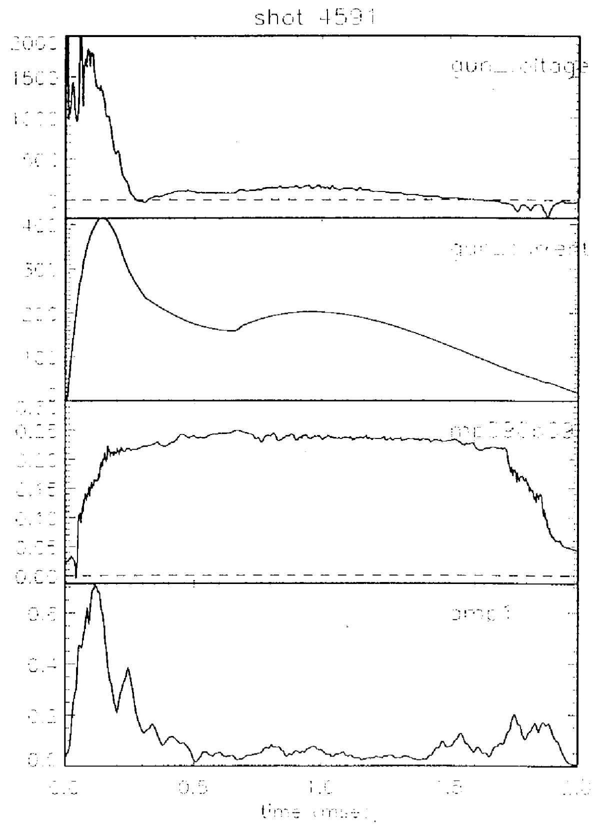

Fig. 2 Time history of sustained plasma

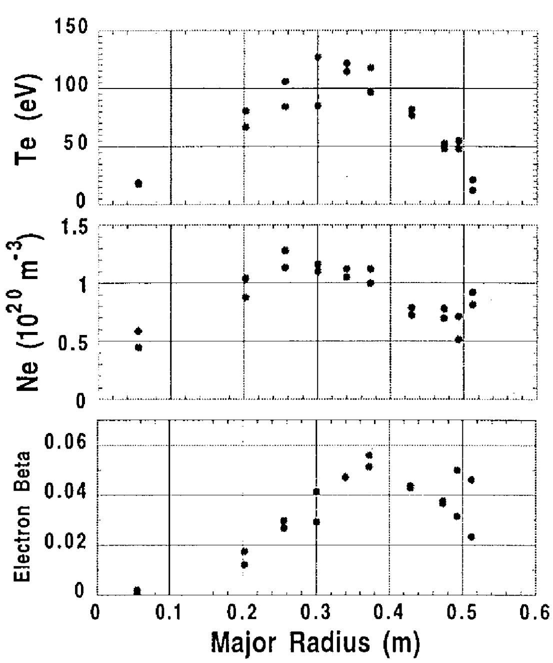

Fig. 3 Electron temperature, density, and pressure profiles from Thomson data.

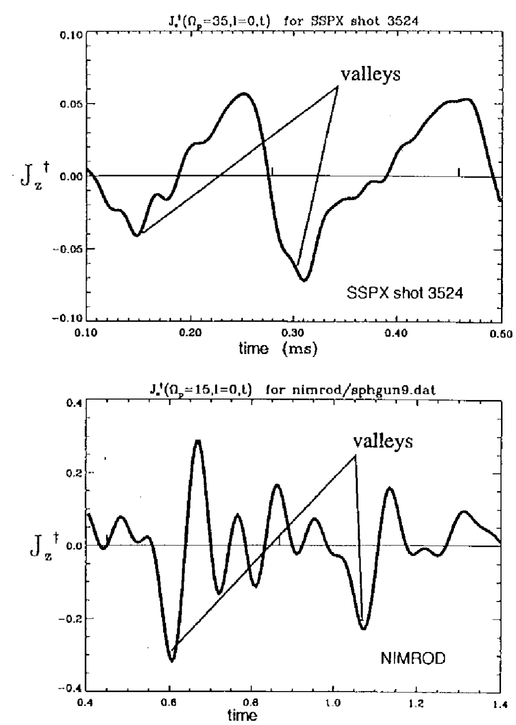

Fig. 4 NIMROD simulation (bot) compared to SSPX data (top) of principle mode driving spheromak plasma.